Available online at www.sciencedirect.com
SciVerse ScienceDirect
Energy Procedia 37 (2013) 4927 – 4936
Energy Procedia

GHGT-11

Cross-international boundary effects of CO_2 injection

Sarah Hannis[a], Stephanie Bricker[a], Aaron Goater[a], Sam Holloway[a], Jeremy Rushton[a],
Gareth Williams[a], John Williams[a]*

[a]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK

Abstract

The Bunter Sandstone Formation in the Southern North Sea is a regional saline aquifer that extends across the median line between UK and Netherlands territorial waters. Numerical simulations of CO_2 injection into a brine-saturated structural closure located in the UK sector have modelled the temporal development of an injection-induced pressure footprint, together with the potential role of faults in brine migration and pressure dissipation in the aquifer. The modelled pressure footprint extends into the Netherlands Sector and if the faults are considered migration pathways, brine expulsion rates of the order of 50 $m^3/day/km^2$ could be expected along the fault zones. This is equivalent to just over 10^5 Ml, during a 50 year injection period, of which approximately 40 % is expelled along a fault beneath Netherlands territorial waters. The simulations have shown that brine displacement will facilitate CO_2 injection into the Bunter Sandstone by alleviating pressure build-up, but an understanding of potential brine migration pathways, rates and environmental impacts must be demonstrated to regulators prior to injection.

Keywords: CO_2 injection; numerical simulation; pressure footprint; brine displacement; Bunter Sandstone; international boundary

1. Introduction

If CO_2 storage is to be deployed at a commercial scale in the UK, large offshore saline aquifers will become targets once depleted hydrocarbon structures have been filled. In this case, pressure effects and brine displacement beyond the boundaries of the CO_2 plume will be important [1], particularly in formations such as the Bunter Sandstone, which is confined above and below by a thick, highly impermeable caprock sequence. Consequently, in formations that span international boundaries, the effect of potential CO_2 injection on neighbouring countries' resources and environment need to be considered.

* Corresponding author. Tel.: +44-1159-363-051; fax: +44-1159-363-200
E-mail address: s.hannis@bgs.ac.uk .

doi:10.1016/j.egypro.2013.06.404

This study models the effect of CO_2 injection into the Bunter Sandstone in the UK sector of the Southern North Sea, close to the median line with the Netherlands. It describes a hypothetical injection scenario into a geological model of a rock volume in part of UK Block 44, and Netherlands block D (Fig 1). The rock volume modelled lies beneath a marine protected area - the Dogger Bank Special Area of Conservation (SAC), a special habitat of shallow submarine sandbanks. The goal of the study was to determine the potential cross-border effects of CO_2 storage in the UK sector close to the median line with the Netherlands. The potential for displaced brine migration to seabed and the development of a pressure footprint in the Netherlands sector were examined. It is not yet clear to what extent CO_2 storage permit areas should include the pressure footprint beyond the maximum extent of CO_2 plume migration (which may be very large but transient). However, Netherlands law prohibits changes to the subsurface pressure regime without a licence.

A 3D static geological model of the potential storage reservoir and surrounding strata was constructed using PETREL. The model was based on a detailed interpretation of 3D seismic data complemented by UK and Netherlands well data. It includes a high resolution 'near-well' part with detailed structure and reservoir heterogeneity around the hypothetical injection well. The remaining 'regional' part of the model includes faults and other structural features, but was assigned homogeneous reservoir properties. Dynamic simulations of CO_2 injection into this model were run using ECLIPSE, a commercial multiphase reservoir simulator, to explore near-wellbore pressure effects. These are compared with dynamic simulations run using a single-phase groundwater flow model, ZOOMQ3D [2]. ZOOMQ3D's faster computational run times allowed a sensitivity analysis of far-field effects over the entire regional model, in particular the sensitivity of brine flux to the seabed via faults to potential fault properties.

2. Methods : Geology and models

2.1 Study area and input data

Fifty-eight UK and 30 Netherlands wells have been drilled in the area of interest, mainly for hydrocarbon exploration in the Lower Permian–Carboniferous reservoirs beneath the Bunter Sandstone. There are 8 wells within the 'near-well' area (Fig 1b) and those with suitable geophysical logs were interpreted to determine net to gross ratios and porosity. The location of 3D seismic reflection data used is shown in Fig 1b.

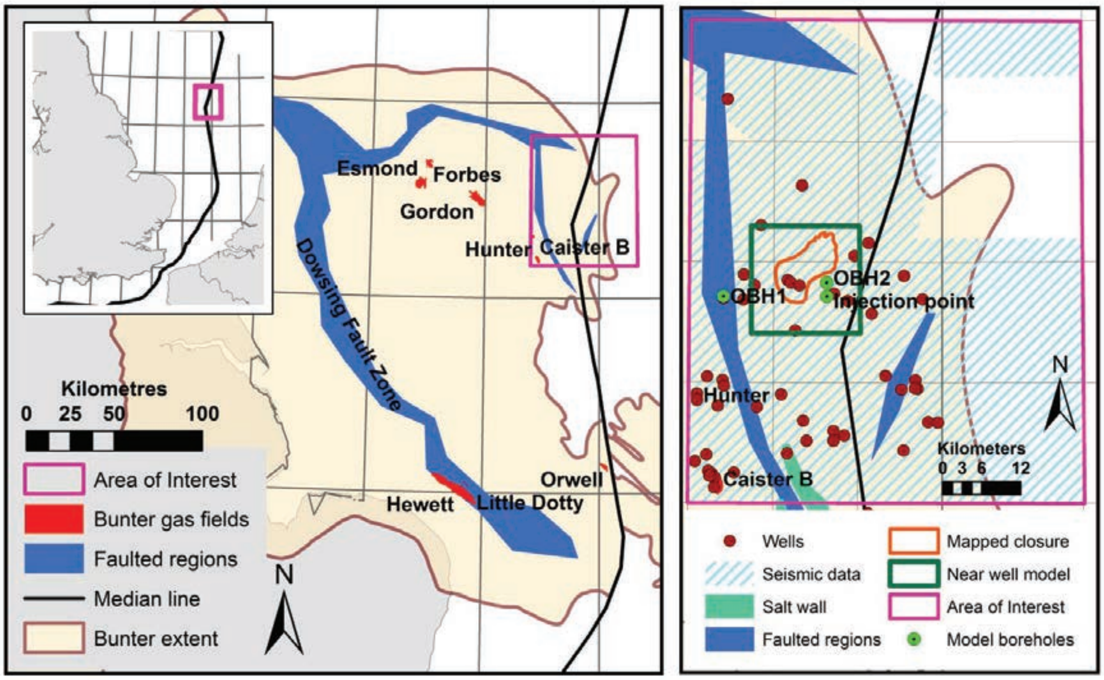

Fig. 1. a) Bunter extent and area of interest b) Area of interest and input data

2.2 Stratigraphy of the Bunter Sandstone and surrounding strata

The Bunter Sandstone is between 80 and 150 m thick in the study area. It is underlain by the Bunter Shale Formation and evaporites of the Zechstein Supergroup, which are expected to form an effective seal at the base of the reservoir. The Bunter Sandstone is overlain directly by a thin mudstone (known as the Solling Formation in Netherlands stratigraphical nomenclature). In the Netherlands sector this unit has a porosity of 2.7 % and a permeability of 0.0065 mD (4.2×10^{-7} m/d) [3]. A salt unit known as the Röt Halite immediately overlies the Solling Formation which is assumed to be completely impermeable. Above these units a thick succession of mudstone, halite and anhydrite make up the remainder of the Haisborough Group, which is generally in excess of 200m thick [4].

Towards the eastern margin of the model, the Base Cretaceous Unconformity cuts down into the Triassic succession so that, in parts of the Netherlands sector, Early Cretaceous mudstones (equivalents of the UK Cromer Knoll Group) rest unconformably on the Bunter Sandstone. These strata provide an effective seal to natural gas in the Orwell gas field (UK block 50/26). Further east, the Bunter Sandstone is truncated against the Cleaver Bank High by the same unconformity.

2.3 Geological structure in the study area

Interpretation of seismic data revealed four Bunter Sandstone closures in the region of interest. The near-well model focused on the largest of these, located mostly in block 44/19. This is a periclinal closure approximately 10 km across. Its spill point (lowest closing contour) is about 4.5 km west of the UK-

Netherlands median line. There are no seismically resolvable faults affecting the Bunter Sandstone or the immediate caprock over the pericline.

The northern and western parts of the area include fault zones, which may or may not act as barriers to fluid flow and the pressure front. These faults could provide potential migration pathways to the seabed or shallower stratigraphic units. Some of these features appear to be associated with salt walls or salt-filled fracture zones, through which it seems unlikely that fluids could pass laterally. However, due to their complexity, the vertical hydraulic properties of these faults are regarded as a significant uncertainty in the model. A major NW-SE-oriented salt wall up to 45 km in length and 5 km in width is present to the south of the study area, the northern part of which is shown in Figure 1b. This is expected to provide a natural flow barrier to the south and west of the area of interest. Two major faults have been mapped in the Netherlands Sector of the area of interest, which on seismic reflection data appear to be linked and extend up to the sea bed. The faults and salt features described above are included in the model. In the sensitivity analysis the faults are treated as either sealing (in which case they could act as pressure/fluid flow barriers) or non-sealing (in which case they could act as potential conduits to the sea bed) in order to examine possible pressure and brine displacement effects, including potential brine fluxes to the sea bed.

Some 115 km west and southwest of the area of interest the NW-SE trending Dowsing Fault Zone (Fig 1a) has significant fault displacements, which may juxtapose the Bunter Sandstone with mudstone units. The Bunter Sandstone east of this zone is characterized by very high salinities and periclines formed above Zechstein salt domes [5]. This zone is used to delineate the ZOOMQ3D model boundary.

2.4 Reservoir properties of the Bunter Sandstone in the study area

The Bunter Sandstone is composed of heterogeneous sheet-flood-dominated sandstones and fluvial clastic sediments deposited on an alluvial braidplain [6,7]. The distributions of reservoir properties are dependent on the original lithology, which was subsequently affected by sediment re-working and diagenetic processes. Reservoir properties are therefore highly variable and difficult to predict with confidence. However detailed log correlation is possible in the near-well model area, indicating that persistent sub-horizontal layering is prevalent through the unit.

No core samples are available from the Bunter in the area of interest. The log-derived average porosity in the near-well area is 17% and the average net to gross ratio is 0.7. Porosity measurements from regional core sample analyses show significant scatter around an arithmetic mean value of 19 % within a range of 2 % to 35 %. For the same data set, the geometric mean permeability (to air) is 41 mD (0.0652 m/d), with the full range of values covering several orders of magnitude (0.01 – 10000 mD; 6.4×10^{-5} – 6.5 m/d). Vertical permeability values are approx 30 % lower than the horizontal permeabilities. There is no clear trend between porosity and depth. Halite and anhydrite cements are common.

2.5 The 'near-well' static geological model

A 16 x 17 km 'near-well' geological model was built over the largest Bunter Sandstone closure in the area of interest (50 m horizontal cell resolution). Depth to the crest of this structure is 1670 m. The top and base of the Bunter Sandstone were interpreted from the 5 wells with geophysical logs in the model area. The well picks were extended throughout the model based on interpreted 3D seismic data and depth converted using a simple layer-cake velocity model. Reservoir thickness is on average 111 m and it was divided vertically into 7 zones, based on correlations between Netherlands stratigraphic nomenclature and the Caister B field [8,7] in the 5 wells. The basal zone (zone 7) is a relatively thin shaley unit, overlain by a fairly thick homogeneous cleaner sandstone unit (zone 6), most likely composed of sheetflood deposits. Above this, zones 5–1 are thinner and more mixed units which may have been deposited in braided river channels. Each zone was subdivided into layers, to give 68 vertical cells c. 2m thick. In total the near-well model has 7.7 million cells. This allowed incorporation of as much geological detail as possible, given the resolution and distribution of the input data.

Porosity and shale volume were interpreted from logs in the 5 wells and upscaled into the model grid. The grid was populated with porosity using stochastic modelling with large variograms, reflecting the fact that geophysical logs can be readily correlated between wells and geological properties are likely laterally consistent. The grid was populated with permeability using a regional core porosity – permeability relationship. The arithmetic average porosity of the model was 13% (range 0 – 36.2%), and the geometric mean permeability was 7.3 mD (range 0.0065 - 8995 mD).

2.6 The 'regional' static geological model

In order to model the far-field pressure effects a grid was built over a much larger area, from the eastern limit of the Bunter to the Dowsing Fault Zone (~160 km x 230 km). A 'tartan' grid was used in order to reduce the cell count for dynamic modelling. This gridding scheme allowed for a close-spaced grid in the near well zone (333 m cells), with progressively larger cell size (1 km, 3 km and 9 km) further away (Fig 2b). Top and Base Bunter Sandstone surfaces were extended by extrapolating between well and seismic data.

This regional model also included a layer of 2 cells above the reservoir to represent the Solling Formation caprock. These were assigned a 42 m thickness in total, based on the average thickness of the Solling across the near-well model area, and assigned the average property values from Spain & Conrad, [3] (Section 2.3).

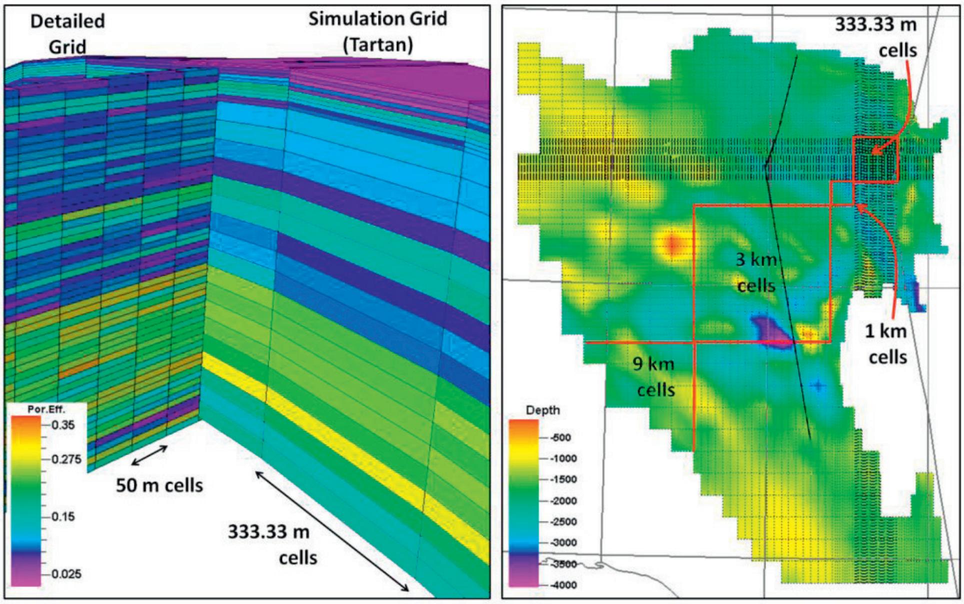

Fig. 2. a) Upscaling grid properties from near-well to regional model for simulation b) Plan view of simulation tartan grid showing cell sizes

The vertical gridding in the regional model incorporated thin cells towards the top of the reservoir to allow a thin buoyant CO_2 tongue to be resolved. Porosity and permeability properties from the detailed near-well geological model were upscaled into the regional model using a proprietary PETREL flow-based algorithm to give permeabilities in x,y,z direction (fig 2a). Outside the near well zone homogenous porosity and permeability values were assigned based on either the near well average or the geometric mean of measured coreplug porosity and permeability values (see Table 1). In reality a gradient between the two is likely, however a detailed study is outside the scope of this contribution.

Model boundaries were assumed to be closed (due to Bunter Sandstone being absent, or the presence of the Dowsing Fault Zone). Cells penetrated by the faults or salt walls described in section 2.2 (Figure 1b) were included in the model and set to open or closed in order to address uncertainty regarding pressure compartmentalisation.

Four model iterations were run to represent 'end member' scenarios (Table 1). In models 1 and 2, the porosity is the arithmetic mean of the upscaled near-well model and permeability is the geometric mean of the upscaled near-well model. In models 3 and 4, the porosity is the arithmetic mean of all UK Bunter Sandstone core data and permeability the geometric mean of all UK Bunter Sandstone core data.

Table 1 showing 4 model iterations with differing homogeneous properties used to populate the outer grid cells.

Model	Data source for outer region	Permeability outside near-well region	Porosity outside near-well region	Faults present
1	Near-well model	7.3mD	13%	Yes
2	Near-well model	7.3mD	13%	No
3	Regional core data	41mD	17%	Yes
4	Regional core data	41mD	17%	No

3. Results : Dynamic simulation

3.1 ECLIPSE dynamic model

The four regional PETREL static models described in Table 1 were imported into ECLIPSE 300 to run the CO_2 injection simulations. The aim was to provide pressures and pressure change information from the four models just outside the CO_2 plume extents (i.e. in the single phase brine saturated zone) to use as input in the ZOOMQ3D simulations. Model parameters and pressure outputs were matched in the two software packages where possible, to allow for comparison between the two codes.

CO_2 injection was simulated through one well, downdip of the dome crest in a high permeability region (Figure 1b). An injection rate of 1.5 Mt/yr was used over the full height of the reservoir. This was modelled for 50 years injection, followed by 150 years relaxation (i.e. 200 years in total). Pressure responses after 50 years (end of injection) are displayed in Figure 3. This shows that the maximum pressure change occurs at the injection well in all models (Figure 3a) and ranges from ~9 MPa in model 1 to 4.6 MPa in model 4. From Figure 3 it appears that the overall size or footprint of the area affected by a pressure change is somewhat similar for each model (because of the colour scaling). However the width of the footprint through the injection well where the pressure drops to < 0.1 MPa is about 65 km for model 2 and about 83 km for model 4. The vertical pressure gradient was not significant in each model run.

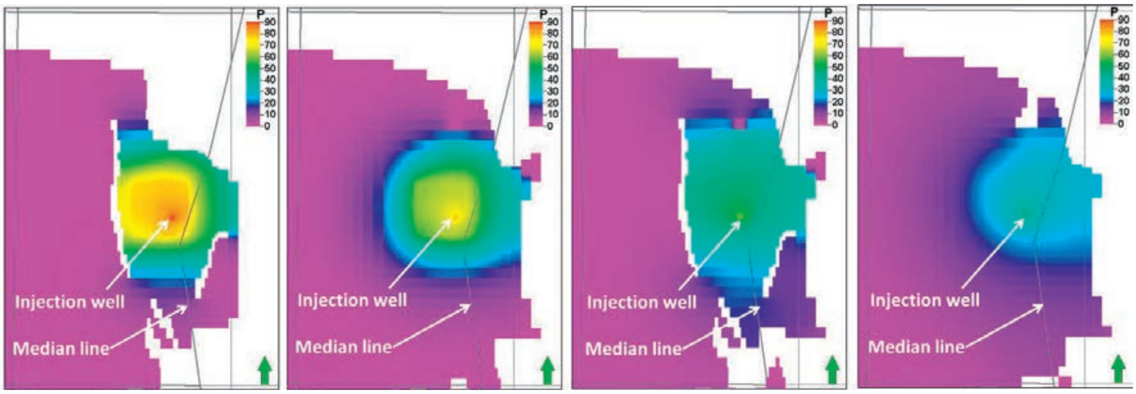

Fig. 3. ECLIPSE pressure change after 50 years CO_2 injection. a) to d) Model numbers 1-4 refer to table 1. Quad block is 65 km by 111 km.

Models 1 and 2 have lower near-well porosity and permeability than models 3 and 4, which were populated with the higher regional core data averages. These models thus represent a ‘worst case scenario’, and it is clear from the flow simulations that there is increased pressure build up in the near well zone, with a smaller pressure footprint. However, because the pressure footprint is smaller, the potential area that could be affected by brine migration is reduced. The presence of faults acting as barriers restricts the pressure footprint (models 1 & 3), compared to the scenarios where they are absent (2 & 4). In all model runs, the pressure plume extends into the Netherlands sector, and had not significantly dissipated after 200 years (because the model has closed boundaries). Maximum pressure changes in the Netherlands Sector are ~7.9 MPa and ~3.2 MPa for models 1 and 4 respectively, at 50 years from the start of injection.

3.2 ZOOMQ3D dynamic model

The ZOOMQ3D model [2] is a simple one-layer model with the aquifer top and base defined by the thickness of the sandstone. The model uses a coarse grid with a 2500 m cell size over the wider extent and a refined grid with a 500 m cell size closer to the area of interest (Figure 4a). As far as possible, the same model parameters and injection scenarios were used as for ECLIPSE model 4 (Table 1): injection of 1.5 Mt/yr CO_2 through 1 well (adjusted groundwater equivalent 6 Ml/d) for 50 years with no-flow boundaries and confined aquifer conditions. Pressure data at two observation boreholes (OBH 1 and OBH2 (Figure 1b)) were used to validate modelled pressure data against ECLIPSE outputs. Model 4, where the outer model is populated using the regional core data averages, gave the best match (Figures 3d and 4b).

Model 4 was used to assess the extent of pressure build up due to CO_2 injection and to assess the potential for displacement of brine out of the system. The displacement pathways considered here are faults. Future work plans include studies of abandoned wells as pathways.

Table 2 - Summary of ZOOM models

Model	Fault behaviour	Fault hydraulic conductance (permeability)	Total sea bed surface brine flux
4.0 (base case)	Absent	N/A	None
4.1	Barriers	$1.3x10^{-9}$ m/d (~10^{-6} mD)	None
4.2	Conduits	0.0652 m/d (41 mD)	56 $m^3/d/km^2$ (average rate over 50 years injection)

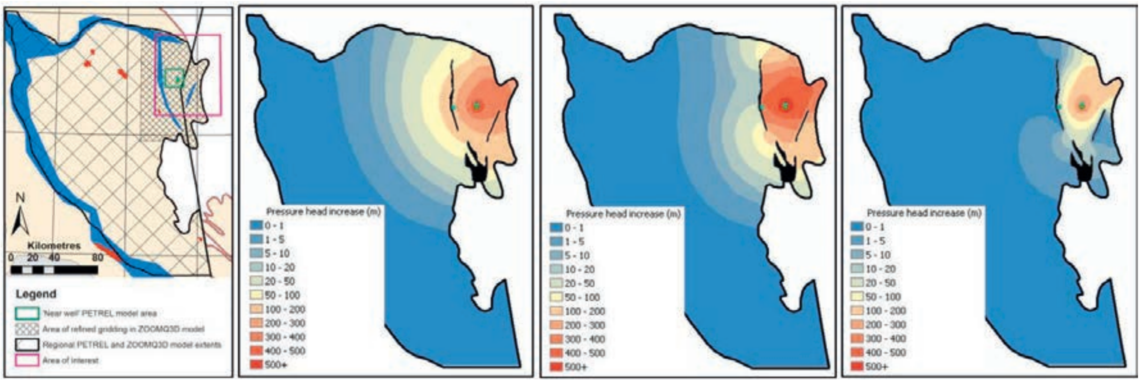

Fig. 4. a) location of ZOOMQ3D model and grid refinement areas. b-d) show pressure head increase as a result of CO_2 injection for models 4.0 (b), 4.1 (c) & 4.2 (d) at the end of injection (50 yrs). Note that 1MPa = 101.97 m pressure head. Black lines show the position of faults. The irregular black shape is a salt wall feature. The green circle indicates the injection well location. The blue circle closest to the injection well is OBH1. OBH2 is the blue circle near the fault zone (refer to Fig 1b).

The width of the pressure plume (measured through the injection well, to the point at which the pressure heads drop to <10 m (<0.1 MPa, equivalent to the measurements taken in section 3.1) is about 84 km for model 4.0 (equivalent to the matched ECLIPSE model 4), about 62 km for model 4.1 and 38 km for model 4.2.

In the base case (Model 4.0, Figure 4b) groundwater pressure head increases at OBH2 (near to the faults in the UK sector) approach 180 m (equivalent to 1.77 MPa) as a result of the injection, peaking 18 months after the cessation of injection. Pressure heads recover in the post injection period (30 years), but remain at least 100 m (0.98 MPa) above initial pressure conditions.

In model 4.1 (Figure 4c), the faults are modelled as barriers to groundwater flow (Table 2) by assigning them a very low hydraulic conductivity (1.3×10^{-9} m/d, approximately10^{-6} mD). Groundwater pressure heads are increased close to the injection well as a result of the faults. At OBH 2, which is located near to the UK fault, pressure heads are some 200 m higher than model 4.0 where faults were not modelled, while pressure heads at OBH1, next to the injection well were approximately 100 m higher (equivalent to 1.96 and 0.98 MPa respectively). Maximum pressure heads in the Netherlands sector reach 500 m (4.9 MPa). No surface flux out of the system is modelled, so the rate of recovery of pressure heads post-injection is identical to model 4.0 albeit with higher starting heads.

The faults are modelled as conduits to flow in model 4.2 (Figure 4d), and assigned hydraulic conductivities of 0.0652 m/d (41 mD), representative of a clean sandstone (taken from the geometric mean of the permeability in the near-well model) and therefore permit groundwater flow. A series of leakage nodes are present along both of the faults which have a co-efficient of vertical conductance (C_z) of 3.25×10^{-4} m/d (equivalent vertical hydraulic conductivity K_v of 0.065 m/d) to simulate the potential for vertical brine displacement along a conductive fault. A marked reduction in groundwater heads both close to the injection well and away from the injection well near the UK fault is therefore observed (Figure 4d). At OBH2 groundwater heads are increased by less than 15 m (0.15 MPa) after the 50 yrs injection period as the fault acts as a displacement pathway for pressure dissipation. A similar effect is observed as a result of brine displacement up the fault in the Netherlands. Maximum pressure heads in the Netherlands sector are only 200 m (1.96 MPa), less than half those seen in model 4.1. However significant brine displacement along the fault paths is observed (Figure 5), with approximately 107000 Ml (1.21×10^{11} kg) expelled through both faults during the 80 year simulation period. That is equivalent to 98% of the originally injected volume. Maximum displacement rate is almost 6 Ml/d (2.19 million m^3/yr). Note that 6

Ml/day is the adjusted groundwater equivalent amount of CO_2 injected into the system). Figure 5a shows the time lag for the modelled surface expulsion rate to tend towards the injection rate. This time lag is due to brine and rock compressibility. In reality, CO_2 compressibility (not taken into account in this version of the single phase model) will further increase the time lag. With a fault zone of 88 km^2 the maximum brine expulsion rate is 68 $m^3/d/km^2$ while the average is 56 $m^3/d/km^2$ during the 50 yrs injection period.

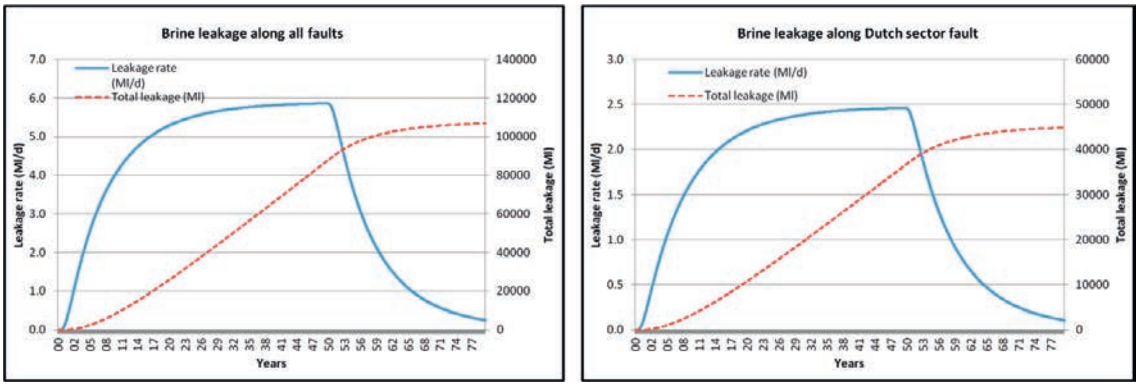

Fig 5 brine expelled along a) all faults in the model b) Netherlands Sector fault (for fault locations see Fig 4).

Total brine expelled at the seabed along the fault within the Netherlands sector is ~45,000 Ml ($5.1x10^{10}$ kg) during the 80 year simulation period with a maximum expulsion rate of nearly 2.5 Ml/d (0.91 million m^3/yr). The area of seabed along the Netherlands fault zone is 28.75 km^2. This gives a maximum brine flux of 87 $m^3/d/km^2$ and an average brine flux of 72 $m^3/d/km^2$ during the 50 yr injection period.

4. Conclusions

With 1.5 Mt/yr injection through 1 well for 50 years, the maximum pressure increase in the scenarios modelled was 9.2 MPa at the injection well. The pressure footprint extends into the Netherlands Sector, with maximum pressure increases of 2-8 MPa at, or shortly after, the end of the injection period. Sensitivity analyses to the bulk reservoir porosity and permeability found that using lower values increased the maximum pressure changes but reduced pressure footprint size. Sensitivity analyses of the vertical conductance (permeability) of the faults produced seabed flux rates of expelled brine of the order of 70-80 $m^3/d/km^2$. The maximum modelled expulsion rate from faults is ~6 Ml/d (2.19 million m^3/yr, of which almost 2.5 Ml/day (0.91 million m^3/yr) is from the fault in the Netherlands sector. This is a relatively small amount compared with the 175 million m^3 of produced brine released into the UK sector of the North Sea in 2011 [9]. However, brine emerging from a fault might mix less quickly with surrounding seawater and therefore could potentially have a greater ecological impact. Increasing the vertical hydraulic conductivity of the faults allows increased brine displacement but lowers the size of the pressure footprint by more than half in the scenarios modelled (from 84 to 38km). Brine displacement up faults alleviates pressure build up in the same way that pressure management wells facilitate CO_2 injection. However, although displacement rates can be estimated through modelling, an understanding of potential environmental impacts may need to be demonstrated to regulators. Future work on the impact and dispersion of brine in the seawater is planned along with investigations of potential brine displacement or leakage via other pathways including abandoned wells. Results suggest that if CO_2

injection is carried out near the UK median line in the Bunter Sandstone at the modelled location, pressure perturbations of several MPa will occur in the Netherlands subsurface for which a license would be required in addition to a UK storage permit.

Acknowledgements

This paper is published with the permission of the Director of the British Geological Survey (Natural Environment Research Council). 3D seismic data was kindly provided by PGS, UK, facilitated by Richard Lamb and others. Thanks to colleagues at TNO, the Netherlands for discussion of cross border issues, correlations and fault properties.

References

[1] Cavanagh A, Wildgust N. Pressurization and brine displacement issues for deep saline formation CO_2 storage. *Energy Procedia* 2011; **4** 4814-4821.

[2] Jackson CR, Spink AEF. *User's manual for the groundwater flow model ZOOMQ3D.* Internal Report IR/04/140: British Geological Survey, 2004.

[3] Spain DR, Conrad CP. Quantitative analysis of top seal capacity: offshore Netherlands, southern North Sea. Geologie en Mijnbouw 1997;**76**:217-226.

[4] Heinemann N, Wilkinson M, Pickup GE, Haszeldine RS, Cutler NA. CO_2 storage in the offshore UK Bunter Sandstone Formation. International Journal of Greenhouse Gas Control 2012; **6**:210-219.

[5] Noy DJ, Holloway S, Chadwick RA, Williams JDO, Hannis SD,.Lahann RW. Modelling large-scale carbon dioxide injection into the Bunter Sandstone in the UK Southern North Sea. International Journal of Greenhouse Gas Control 2012;**9:**220-233.

[6] Bifani R. Esmond Gas Complex. In: Brooks J, Goff JC, van Hoorn B, editors. *Habitat of Palaeozoic Gas in N.W. Europe, Geological Society Special Publication No. 23*, 1986, p. 209-221.

[7] Ritchie JS, Pratsides P. The Caister fields, Block 44/23a, UK North Sea. In: Parker JR, editor. *Petroleum Geology of Northwest Europe: Proceedings of the Fourth Conference*, Geological Society, London. 1993, p. 759-769.

[8] Geluk MC, Rohling H-G. High-resolution sequence stratigraphy of the Lower Triassic 'Buntsandstein' in the Netherlands and northwestern Germany. Geologie en Mijnbouw 1997;**76**:227–246.

[9] Department of Energy & Climate Change (DECC) Produced water discharges containing oil (2005-11). Accessed 2012. og.decc.gov.uk/en/olgs/cms/data_maps/field_data/oil_discharged/oil_discharged.aspx